

## GOATS 2008

### Autonomous, Adaptive Multistatic Acoustic Sensing

PI: Henrik Schmidt  
Massachusetts Institute of Technology  
77 Massachusetts Avenue  
Room 5-204  
Cambridge, MA 02139  
Phone: (617) 253-5727 Fax: (617) 253-2350 Email: [henrik@mit.edu](mailto:henrik@mit.edu)

CoPI:Arjuna Balasuriya  
Massachusetts Institute of Technology  
77 Massachusetts Avenue  
Room 5-207  
Cambridge, MA 02139  
Phone: (617) 324-1461 Fax: (617) 253-2350 Email: [arjunab@mit.edu](mailto:arjunab@mit.edu)

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#### **LONG-TERM GOALS**

To develop net-centric, autonomous underwater vehicle sensing concepts for littoral MCM and ASW, exploiting collaborative and environmentally adaptive, bi- and multi-static, passive and active sonar configurations for concurrent detection, classification and localization of subsea and bottom objects..

#### **OBJECTIVES**

The MIT Laboratory for Autonomous Marine Sensing Systems (LAMSS) has continued its interdisciplinary research under the GOATS project, initiated in 1998 in collaboration between MIT and NURC, and as such a seamless continuation of the research effort under the previous grant N00014-05-1-0255. The principal objective is to develop, implement and demonstrate real-time, onboard *integrated acoustic sensing, signal processing and platform control* algorithms for adaptive, collaborative, multiplatform REA, MCM, and ASW in unknown and unmapped littoral environments with uncertain navigation and communication infrastructure.

A related objective is the development of a nested, distributed command and control architecture that enables individual network nodes or clusters of nodes to complete the mission objectives, including target detection, classification, localization and tracking (DCLT), fully autonomously with no or limited communication with the network operators. The need for such a nested, autonomous communication, command and control architecture has become clear from the series of experiments carried out in the past under GOATS and several experiments carried out under the UPS PLUSNet program.

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## APPROACH

The GOATS (Generic Ocean Array Technology Sonar) research program is a highly interdisciplinary effort, involving experiments, theory and model development in advanced oceanography, acoustics, signal processing, and robotics. The center-piece of the research effort has been a series of Joint Research Projects (JRP) with the NATO Undersea Research Centre (NURC). The joint effort was initiated with the GOATS' 98 pilot experiment [1] and continued with the GOATS' 2000 and BP02/MASAI02 experiments. Currently the collaboration is being continued under a NURC JRP on sensing network technology. In addition to the field experiments involving significant resources provided by NURC, GOATS uses modeling and simulation to explore the potential of autonomous underwater vehicle networks as platforms for new sonar concepts exploring the full 3-D acoustic environment of shallow water (SW) and very shallow water (VSW).

The fundamental approach of GOATS is the development of the concept of a network of AUVs as an array of *Virtual Sensors*, based on fully *integrated sensing, modeling and control*, reducing the inter-platform communication requirements to be consistent with the reality of shallow water acoustic communication in regard to low bit-rate, latency and intermittency. Thus, for example the past GOATS effort has demonstrated that platform motion information can be used for clutter control by providing geometric constraints to on-board detection algorithms, reducing the communication requirements to location, POD, and classification information. Conversely, on-board sensor fusion and processing can be fed back to the vehicle control system for autonomous, adaptive sampling – again with the potential for significantly enhanced POD/PFA performance.

In regards to applications to MCM, GOATS explores the use of bi-static and multi-static Synthetic Aperture created by the network, in combination with low frequency (1-10 kHz) wide-beam insonification to provide coverage, bottom penetration and location resolution for concurrent detection, localization and classification of proud and buried targets in SW and VSW. The signal processing effort is therefore centered around generalizing SAS processing to bi-static and multi-static configurations, including bi-static generalizations of auto-focusing and track-before-detect (TBD) algorithms. Another issue concerns the stability and coherence of surface and seabed multiples and their potential use in advanced low-frequency SAS concepts.

More recently, the GOATS effort has transitioned towards the development of similar, autonomous network concepts for passive littoral surveillance, e.g. the Undersea Persistent Surveillance (UPS) program, initiated in 2005 and completed in 2008. PI Schmidt was lead PI and Chief Scientist for the UPS PLUSNet Program, which developed a network concept of operations based on clusters of AUV and gliders, connected via acoustic communication, and intermittent RF communication with the operators through periodically surfacing gliders. A prototype network concept with a hybrid, cooperating suite of underwater and surface assets was successfully demonstrated in PN07 in Dabob Bay, WA. As in the past GOATS effort, the MIT marine autonomy effort is utilizing the open-source MOOS control mission control software originally developed and funded under GOATS. To take advantage of the robustness of the native control software, while at the same time retaining the flexibility in regard to sensor-driven adaptation and collaboration, MIT LAMSS has developed a new nested control architecture, where the lower level control of the nodes, as well as the overall field control can be performed using arbitrary third-party software, while the medium level, adaptive and collaborative control of the nodes and the clusters is performed within the MOOS software framework [2].

Such a nested command and control infrastructure with heterogeneous assets invariably need translation to and from a common communications protocol. Starting with the MB'06 experiment, MIT and Bluefin AUVs were controlled using a new, so-called “back-seat driver” paradigm wherein low-level commands to the Bluefin control software were translated and conveyed by a specially designed MOOS module.

The mid-level, adaptive and collaborative control of the network nodes is carried out using MOOS in combination with the new multi-objective, behavior-based IvP control framework developed within MOOS by Michael Benjamin at NUWC/MIT. The core of this architecture consists of a behavior-based control system which uses multiple objective functions to determine the appropriate course, speed, and depth of the platform at every control cycle (typically 10-20 Hz). The desired course of action is determined by computing a multi-function optimization over the objective functions using the Interval Programming Model developed by Benjamin which provides a very fast optimization suitable for small vehicles [2].

The development of GOATS concepts, including PLUSNet, is based heavily on simulation, incorporating and integrating high-fidelity acoustic modeling, platform dynamics and network communication and control. In regard to the environmental acoustic modeling, MIT continues to develop the OASES-3d modeling framework for target scattering and reverberation in shallow ocean waveguides. As has been the case for the autonomous command and control, recent emphasis has been towards the simulation of passive DCLT by the PLUSnet network. As was previously the case for the MCM effort, the approach has been to develop a complete system simulation capability, where complex adaptive and collaborative sensing missions can be simulated using state-of-the-art, high-fidelity acoustic models for generating synthetic sensor signals in real time. As in the past, this has been achieved by linking the real-time MOOS simulator with the SEALAB acoustic simulation framework, which in ‘real-time’ generates element-level timeseries using Green’s functions using legacy environmental acoustic models such as OASES, CSNAP, and RAM. This new unique simulation environment allows for full simulation of adaptive DCLT missions for the MIT/Bluefin AUVs towing hydrophone arrays, incorporating correlated and directional ambient noise, and signals generated by moving surface ships and targets

## WORK COMPLETED

### *GLINT'10 Experiment*

MIT LAMS participated in the GLINT'10 experiment, carried out jointly with the NATO Undersea Research Centre in the Tuscan archipelago July 26 – August 16, 2010. MIT operated the Unicorn AUV and the topside command and control infrastructure onboard R/V Alliance, carrying out a series of experiments for adaptive, collaborative autonomy for environmental assessment and for testing of new components of the MOOS-IvP autonomy infrastructure and the unified command and control infrastructure. The MIT AUV was operating in a common undersea network with two NURC Ocean Explorer (OEX) vehicles, operating the same MOOS-IvP payload autonomy architecture as the MIT vehicles. In addition to the physical vehicles, a virtual AUV was operated by MIT LAMSS, fully integrated in the network via a modem deployed from R/V Leonardo. This virtual vehicle was used to demonstrate more risky autonomous behaviors, such as a new collision avoidance behavior where the AUV is changing depth to avoid surface ships, the AIS-reported location of which were transmitted to the AUV via the acoustic modem. Figure 1a shows the MIT topside display of a successful demonstration of this behavior in GLINT'10. The virtual AUV, Macrura is performing a track-and-

trail behavior with the physical Unicorn AUV, and is accidentally passing close the R/V Leonardo, fully autonomously changing its depth from the survey depth of 5 m to 20 m while passing under the ship. Figure 1b shows another demonstration of the combined use of the physical and virtual vehicles. The AUV Unicorn is performing an adaptive thermocline mapping mission, with the vehicle trail shown in green. Note the autonomous collision avoidance for first R/V Leonardo, and subsequently for R/V Alliance. A simultaneous simulation of the intended pentagon survey is shown by the yellow trail. In this case the simulation is detached from the physical network, and the position of the research vessels is unknown to the simulated vehicle, which is therefore not reproducing the collision avoidance. The missions illustrated in Fig. 1 are examples of a series of successful demonstrations of collaborative, adaptive autonomy with MOOS-IvP demonstrated in GLINT'10, including

- First field demonstration of a new dynamic behavior spawning capability, where new behaviors are spawned as needed based on the situational awareness provided via the modem network. This new capability allows the network to adapt to unpredictable events such as a surface ship entering the operations area. For example, the location of R/V Leonardo is passed to the AUV's by transmitting the Leonardo's AIS stream received on Alliance via the modem gateway buoy.
- New collision avoidance behavior involving autonomous, adaptive change of depth.
- New robust adaptive behavior for tracking thermocline dynamics.
- First ever demonstration of depth-adaptation for maintaining acoustic modem connectivity, using onboard acoustic channel modeling.
- Robust track-and-trail behaviors demonstrated for collaborative, adaptive thermocline tracking.
- Field testing of new, improved acoustic communication infrastructure, including demonstration of fully dynamic network MAC layer, where each node will fully autonomously detect other vehicles and coordinate the transmission network through appropriate time slotting.



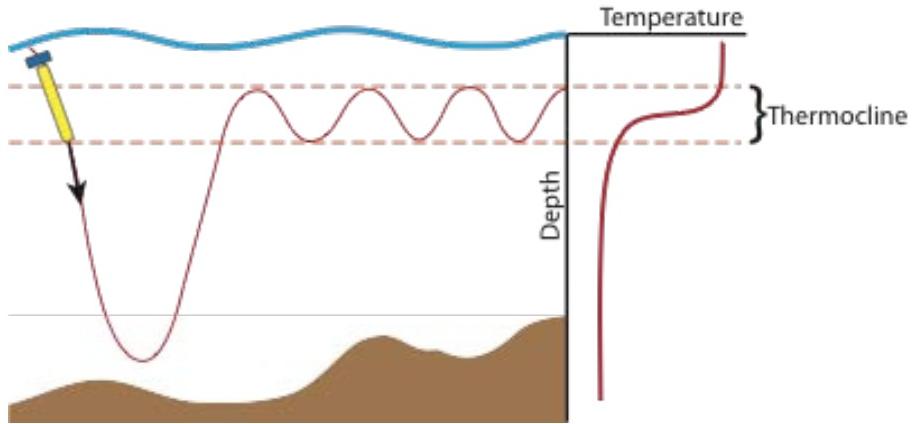
**Figure 1. Demonstration of new dynamically spawned collision avoidance behaviors in GLINT'10 experiment through combined use of physical and virtual AUVs. (a) Depth collision avoidance of R/V Leonardo by a virtual AUV while ‘trailing’ the physical AUV, Macrura. (b) Simultaneous simulation (yellow trail) of thermocline tracking mission by AUV Unicorn (green trail), with the physical vehicle autonomously avoiding collision with first R/V Leonardo, then R/V Alliance.**

## *Autonomous Adaptive Oceanographic Feature Detection and Tracking*

After the initial implementation of autonomous adaptive feature tracking was tested in the GLINT09 experiment (as described in the GOATS 2009 annual report), further testing and improvements of the *pEnvGrad* MOOS process were completed. Over the course of the year, the ability to calculate density and determine the pycnocline depth range were added to *pEnvGrad*, as well as a calculation of the single depth of maximum inflection of the thermocline, halocline, pycnocline, and sound speed over the water column. In addition, the behavior defining the vertical AUV control while yoyo-ing was changed to simplify the means of profiling the water column, as described below. A conceptual example of feature tracking is shown in Figure 2.

The Champlain09 field experiment in Lake Champlain, VT, was conducted in October, 2009, to demonstrate the ability of the *pEnvGrad* MOOS process to allow for completely autonomous tracking of the lake's thermocline (note: a freshwater environment) using an Iver AUV running the MOOS autonomy system. Previous testing of *pEnvGrad* was completed in the highly saline Tyrrhenian Sea near Italy during the GLINT09 experiment, using NURC's much larger OEX AUV running MOOS autonomy to track the depth range of the sound speed maximum. The success of Champlain09 was vital to the demonstration of the portability of *pEnvGrad* as an oceanographic feature detection and tracking algorithm. Due to the differing dive angle and dive speed limitations of various AUVs, the vertical control behavior used to perform the yoyo pattern for thermocline tracking had to be changed. In GLINT09, the vertical control was performed using the Adaptive Environmental Yoyo behavior, *BHV\_AdaptiveEnvtYoyo*, in conjunction with *pEnvGrad* to autonomously adapt the vertical motion of the AUV. During Champlain09, the vertical control was changed to an adaptive Toggle Depth behavior, *BHV\_ToggleDepth*, in which the AUV is either commanded to the upper or lower depth of its vertical yoyo instead of trying to follow a sinusoidal pattern through the water column. This simplification of the vertical control was proven to be a significant improvement during the GLINT10 experiment.

During the GLINT10 field experiment in the Tyrrhenian Sea west of Italy, two of the missions were to detect internal waves in the environment using data sets collected by the autonomous interaction of two AUVs in the water (a Bluefin 21" and a NURC OEX AUV). The first mission involved the OEX performing a pentagonal loiter at 60m depth with the MIT Unicorn (Bluefin 21" AUV) actively trailing 150m behind the OEX at 12m depth (just below the observed thermocline). The purpose of the pentagonal pattern was to be able to distinguish (to a rough estimate) the direction in which any internal waves would propagate. The second mission was similar to the first with the Unicorn trailing the OEX, only this time the OEX was doing a pentagonal loiter at 12m depth while the Unicorn was trailing it and performing adaptive thermocline tracking in the vertical. The thermocline tracking data will be useful in determining the amplitude of any internal waves, as well as providing some frequency information. Finally, a vertical thermistor chain (with 3-meter thermistor spacing from 5m to 30m depth) was strung at the center of the pentagonal internal wave missions to act as a ground-truth for the presence of internal waves.



**Figure 2. Concept of operations for an AUV detecting and tracking a coastal thermocline.**

### Ocean Waveguide Invariants

The so-called waveguide invariant describes striations that often appear in plots of acoustic intensity versus range and frequency in the ocean. The waveguide invariant has been used for passive range estimation (see list of publications), array processing, and digital acoustic communications. The goal of this research is to improve upon the latest understanding of the waveguide invariant and related signal processing. By better understanding the waveguide invariant, we can better determine how an AUV could be used to detect and localize subsea sound sources.

Many sensing methods based on the waveguide invariant assume that “beta=1”, but very little research has investigated why that assumption is often correct (and when it will be incorrect).

We have developed a method for analytically determining how the sound speed profile and seafloor properties affect the value of the waveguide invariant. This method paves the way for determining how an AUV could be controlled in order to best exploit the waveguide invariant. For example, by putting an acoustic receiver at the SSP maximum (which could be adaptively determined by an AUV with a CTD), the waveguide invariant is more likely to have a value of one which can increase the accuracy of passive range estimates.

In addition, array processing methods based on the waveguide invariant have been tested on experimental data from GLINT08 and GLINT10, demonstrating that an array can be used to filter out noise sources while maintaining the striations which could be useful for passive range estimation.

## RESULTS

### Autonomous Adaptive Oceanographic Feature Detection and Tracking

The Champlain09 experiment carried out in Lake Champlain, VT, marked the second successful test of fully autonomous adaptive environmental feature tracking with an AUV. The MIT Laboratory for Autonomous Marine Sensing Systems (LAMSS) worked in conjunction with the Naval Undersea Warfare Center (NUWC) to run MOOS-IvP on the NUWC Iver AUV and employ ‘backseat’ autonomy and behavior optimization. The mission of relevance here is the thermocline tracking mission. The motivation for such a mission was to demonstrate the ability to autonomously detect and track a very

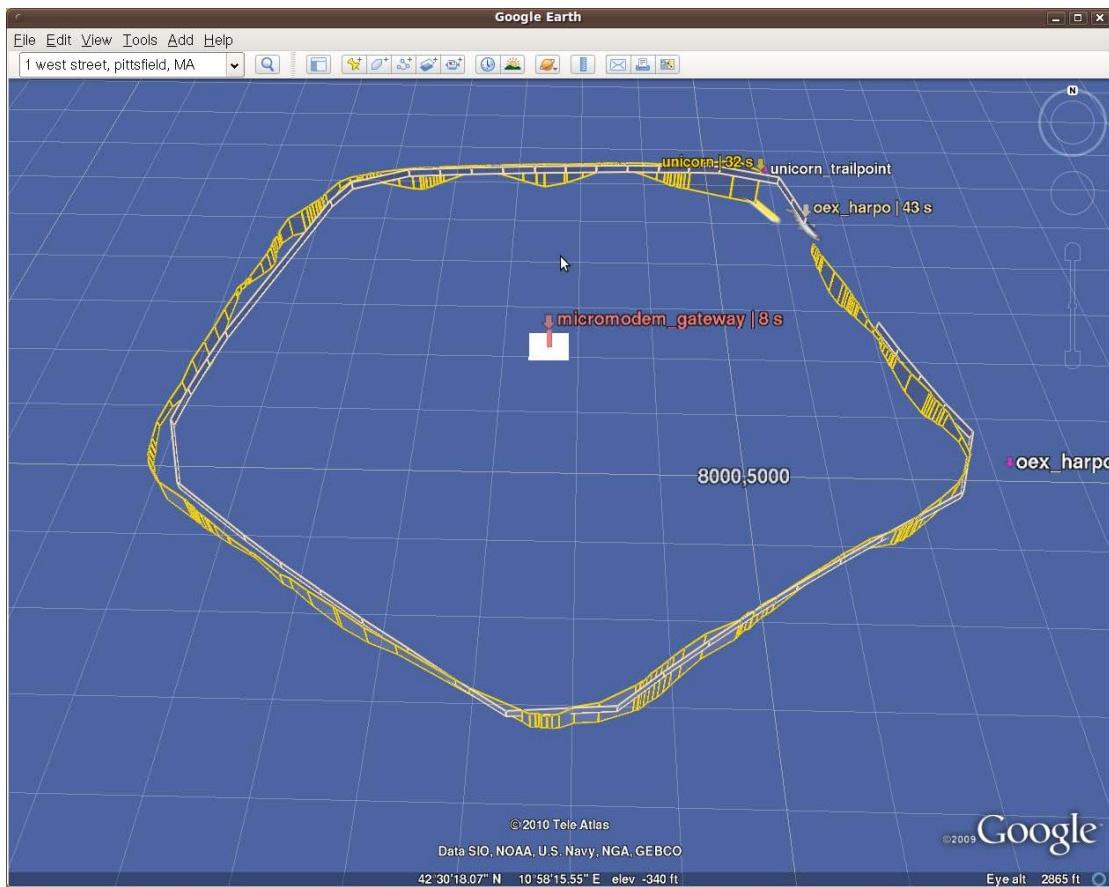
distinct and characteristic coastal oceanographic feature in real-time based on environmental data actively collected and then published to the MOOSDB aboard the AUV. In addition, it demonstrated that the *pEnvGrad* process is easily portable to perform feature (thermocline) tracking in both saline and freshwater environments, on very different AUVs (Iver vs. OEX).

The GLINT10 experiment carried out in the Tyrrhenian Sea north of Porto Santo Stefano, Italy, took thermocline tracking a step further, using it to detect internal waves via two autonomously coordinated AUVs, as demonstrated in 3. The MIT LAMSS worked in conjunction with the NATO Undersea Research Center (NURC) facilitate the autonomous coordination of the MIT Unicorn AUV with the NURC OEX AUV through MOOS-IvP and acoustic communications. The motivation for internal wave detection missions was to demonstrate the advantage of using multiple AUVs coordinating their data collection to capture a more complete data set describing an oceanographic feature. The success of this strategy is demonstrated in 4 and 5, where the moving OEX captured internal wave signatures at 12m depth and the fixed thermistor chain captured them at 11m (the closest thermistor), while all of the other thermistors showed very little or no evidence of internal waves. This is also demonstrated in comparing the temperature signatures of the OEX at 60m (no temperature variation) with the Unicorn trailing at 12m (temperature variations of up to approximately +/- 0.7 degrees Celsius).

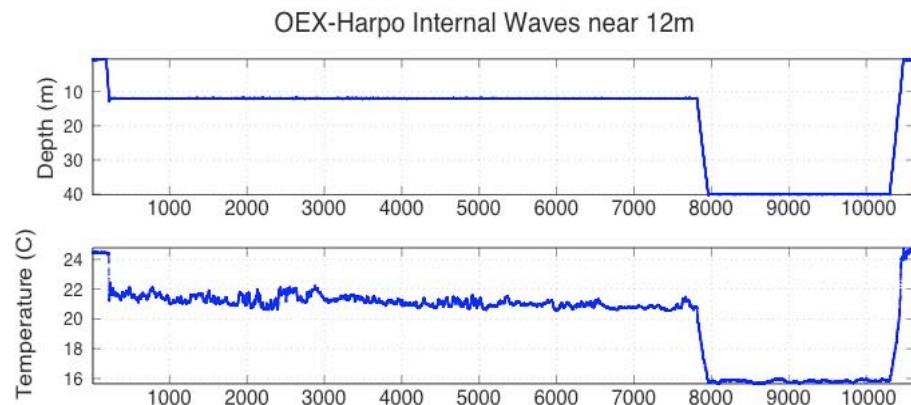
The pre-dive testing of the internal waves missions was accomplished through simulations flying the OEX and Unicorn - driven by MOOS-IvP - through a simulated ocean environment. This environment was updated from bi-daily CTD casts in the operation region, providing good and accurate coverage of the region. Since switching from simulation to runtime is virtually seamless in MOOS-IvP, it was possible to test the full spectrum of how both AUVs would perform and interact autonomously in the water, given a close-to-real-time environment.

### *Ocean Waveguide Invariants*

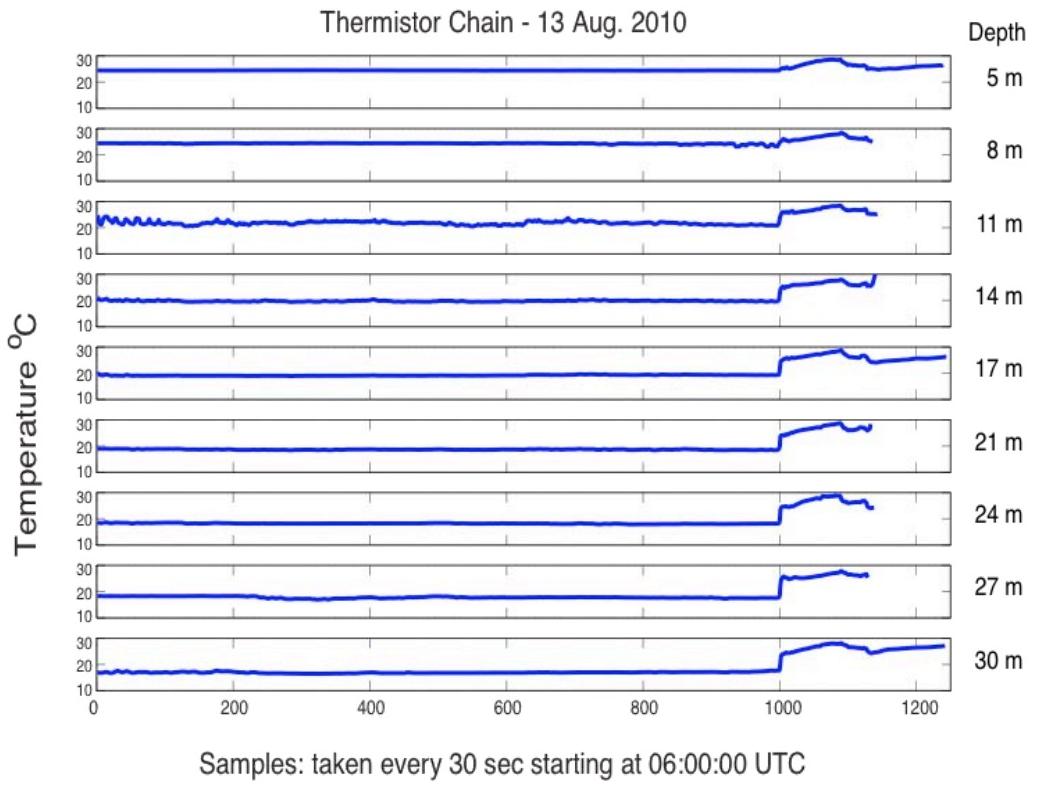
A PhD thesis was completed in 2010 by Kevin Cockrell, providing new understanding of the fundamental physics associated with the waveguide invariant. Figure 6 shows an example of the results obtained, demonstrating the benefits of using a horizontal array aperture for using the waveguide invariant for passive ranging. Fig. 6(a) shows the acoustic intensity as measured from a single hydrophone. Waveguide invariant striations, which point towards the lower left, are present from 350 to 700 Hz. Also present is a noise source with parabolic-shaped striations from 200 to 900 Hz. Fig. 6(b) shows the corresponding result when data from all elements of an array were used to filter out noise coming from directions other than that of the source of interest. As a result, the waveguide invariant striations from the source of interest are much cleaner looking and more amenable to passively estimating the range.



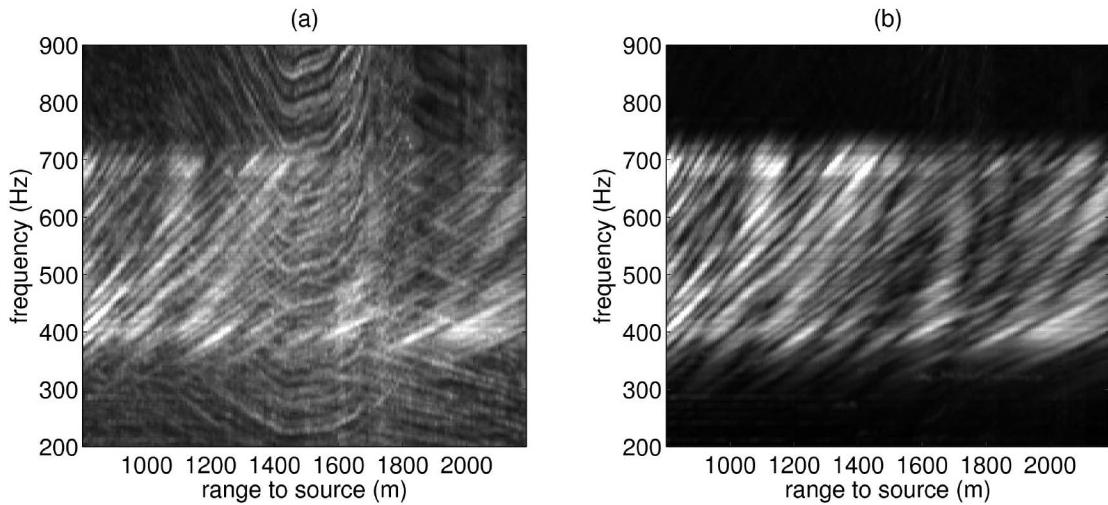
**Figure 3. Internal wave missions.** *Unicorn performing adaptive thermocline tracking (vertical excursions) while trailing the OEX. The OEX is performing a pentagonal loiter at 12m depth, at a radius of ~500m from the Micromodem Gateway Buoy where the thermistor chain is located.*



**Figure 4. Data collected by the OEX AUV during GLINT10,** indicating significant internal wave action near 12m depth (based primarily on temperature fluctuations, since salinity is nearly constant at ~38).



**Figure 5. Thermistor chain data at varying depths, collected during GLINT10.**  
**The strong fluctuations in temperature at 11m suggest the presence of internal waves at that depth (just below the maximum inflection of the thermocline between 9m and 11m).**  
**The temperature spike after  $\sim$ 1000 samples indicates when the thermistor chain was recovered at the end of the internal waves missions.**



**Figure 6: (a) Acoustic intensity as measured from a single hydrophone. (b) Data from all elements of an array were used to filter out noise coming from directions other than that of the source of interest**

## **IMPACT/APPLICATIONS**

The long-term impact of this effort is the development of new sonar concepts for MCM and ASW, which take optimum advantage of the mobility, autonomy and adaptiveness of an autonomous, cooperating vehicle network. For example, bi- and multi-static, low-frequency sonar configurations are being explored for completely or partially proud or buried mines in shallow water, with the traditional high-resolution acoustic imaging being replaced by a 3-D acoustic field characterization as a combined detection and classification paradigm, exploring spatial and temporal characteristics which uniquely define the target and the reverberation environment. Similarly, platform mobility and collaboration is being explored for enhancing DCLT performance of littoral surveillance networks such as PLUSNet.

In 2009, the autonomy developed for sonar concepts were implemented in Rapid Environmental Assessment (REA) missions. Adaptive thermocline tracking was demonstrated with the NURC OEX AUV during the GLINT09 experiment. This autonomy is adopted by the NSF funded Ocean Observatory Initiative (OOI). All the mobile assets under this program will run this autonomy architecture for environmental assessments.

## **TRANSITIONS**

The GOATS'2005 program is a seamless continuation of the now completing GOATS'2005 effort. The progress made in autonomous, multi-AUV, net-centric control, navigation, communication, and collaborative sensing and its implementation into the open-source MOOS-IvP autonomy system architecture is being maintained and distributed by MIT-LAMSS under the GOATS Grant.

In 2010 the MOOS-IvP software architecture operated and distributed originally developed by P. Newman under GOATS funding in 2002) has been chosen at the platform autonomy system baseline for the new DARPA Deep Sea Operations Program (DSOP). It has also been adopted as the basis for a major effort at the NATO Undersea Research Centre (NURC) on the development of autonomous, multi-static active sonar concepts under the 4G4 Undersea Sensing Network Program, as demonstrated in the GLINT10 experiment.

MOOS-IvP is being transitioned to handle the Mission Planning and Control of both moving and fixed assets in the NSF Ocean Observatory Initiative (OOI). Thus MIT is partner in the UCSD led team charged with developing the Cyber Infrastructure for OOI, with responsibility for the MP&C. In addition MIT is taking over the Sensing and Acquisition sub-system under the OOI.

At the core of the MIT LAMSS unified command and control infrastructure for heterogeneous undersea networks is acoustic communications software goby-acomms and its corresponding MOOS application pAcommsHandler [3]. This software infrastructure has begun to see substantial use outside the MIT community in the last year. Outside of the MOOS community, Hanumant Singh's group at WHOI has been evaluating some of the goby-acomms modules for use on the Seabed vehicles. Within the MOOS community, groups at Georgia Tech Research Institute, the NATO Undersea Research Centre, NAVSEA Panama City, and elsewhere have begun to use pAcommsHandler with their autonomous vehicles. At the 2010 MOOS Development and Applications Working Group, we presented a tutorial on pAcommsHandler that was well attended and received. The goby-acomms project has undergone numerous steps to become more accessible and mature, including public code

hosting (<https://launchpad.net/goby>), documentation (<http://gobysoft.com/doc/>), and mailing list ([goby@mit.edu](mailto:goby@mit.edu)).

The seismo-acoustic models developed by MIT are being maintained and disseminated under the GOATS grant. The OASES and CSNAP environmental acoustic modeling codes are used extensively in the ONR sponsored r5esearch at MIT, and continue to be maintained, expanded and made available to the community. The latest addition is a 3D version of CSNAP, which efficiently provides wave-theory solutions for propagation and scattering around seamounts. OASES and CSNAP is continuously being exported or downloaded from the OASES web site, and used extensively by the community as a reference model for ocean seismo acoustics in general.

(<http://acoustics.mit.edu/arctic0/henrik/www/oases.html>)

## RELATED PROJECTS

This effort has constituted part of the US component of the GOATS'2000 Joint Research Project (JRP) with the NATO Undersea Research Centre, and is currently collaborating with NURC under the Autonomous Sensing Networks Joint Research Projects (JRP).

The GOATS program developed out of the ONR Autonomous Ocean Sampling Network (AOSN) initiative completed in FY00, and is strongly related to the continuing AOSN effort. GOATS is also directly related to the Shallow Water Autonomous Mine Sensing Initiative (SWAMSI), initiated in FY04, and currently continuing, and of which MIT is a leading partner.

The Nested Autonomy architecture and acoustic modeling capabilities developed under GOATS has been applied in several other related programs MIT was partnering in, including the now completed AREA (Adaptive Rapid Environmental Assesment) component of the now completed ONR "Capturing Uncertainty" DRI, aimed at mitigating the effect of sonar performance uncertainty associated with environmental uncertainty by adaptively deploying environmental assesment resources. The MOOS-IvP Nested Autonomy architecture developed under GOATS is,together with the AREA concept have been transitioned into the ASAP MURI and the Undersea Persistent Surveillance (UPS) program, with experimental demonstrations in Monterey Bay in MB06 and in Dabob Bay, WA in PN07.

The OASES modeling framework, which is being maintained, upgraded, and distributed to the community under this award, has been used intensively in all the related programs MIT is participating in. The new 3D model of propagation over seamounts [3] is being transitioned and applied to the analysis of the experimental results obtained at Kermit seamount under the NPAL program.

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